Direct photons in pp and Pb-Pb collisions

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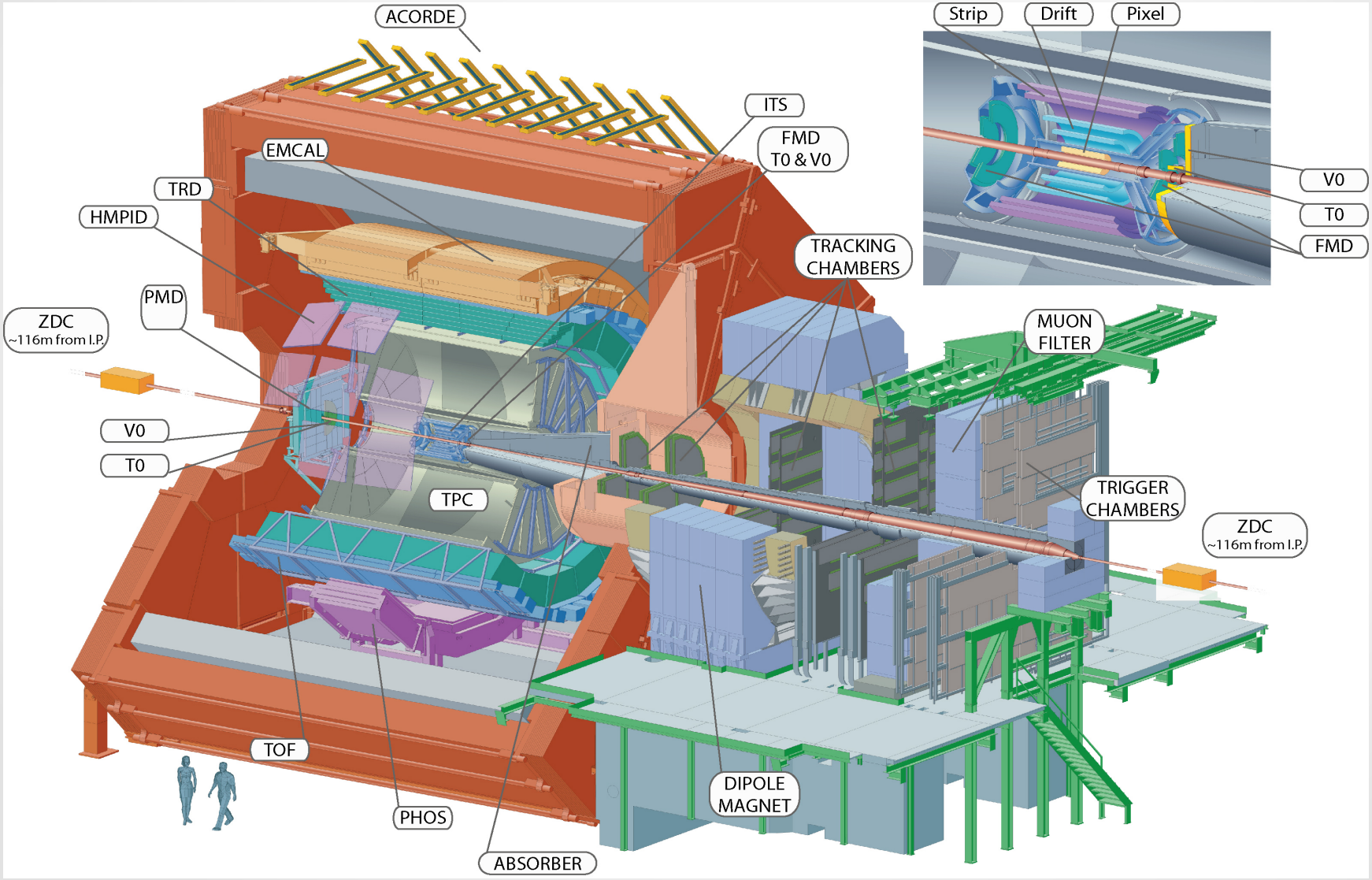
for the ALICE collaboration

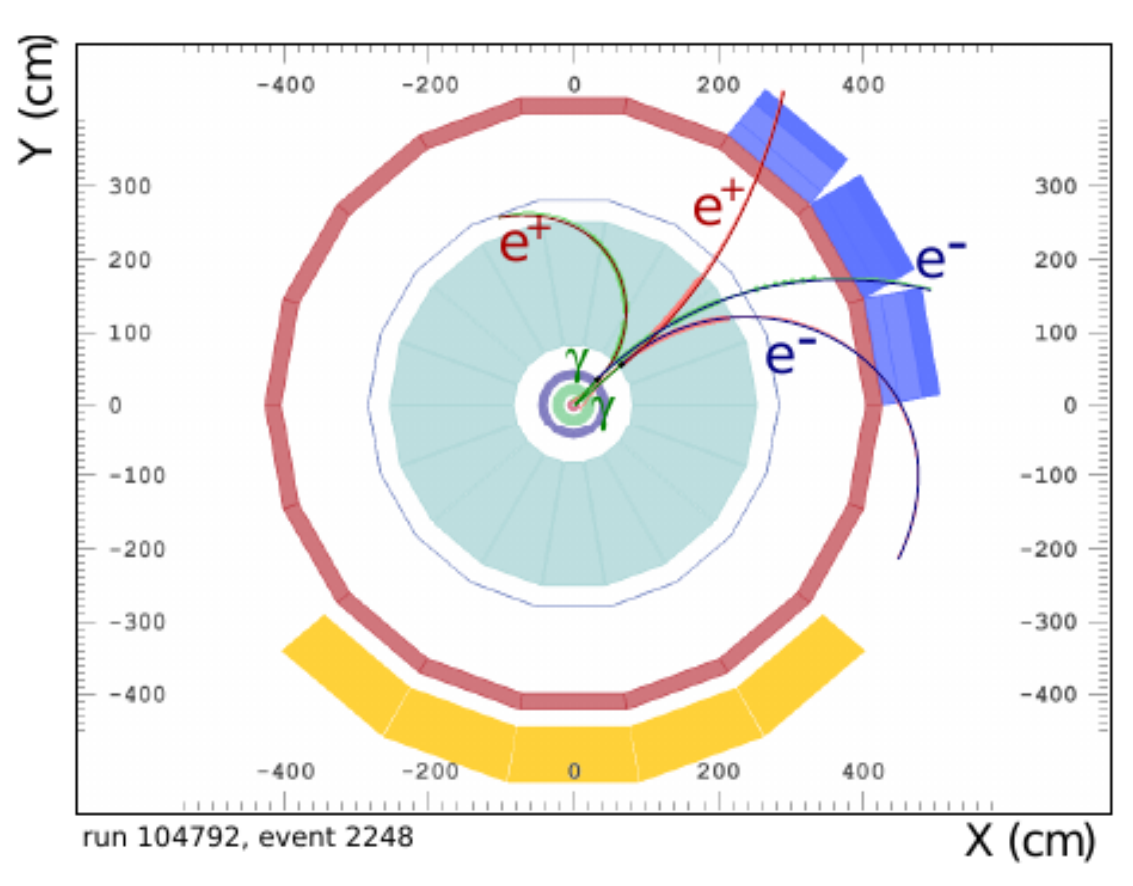
Introduction

- Direct photons provide a tool to test
  - Temperature
  - Collective flow development
  - Space-time dimensions of hot matter
  - Calibration of the initial state
- ALICE peculiarities compared to PHENIX, STAR, WA98
  - Higher temperature => Higher thermal photon yield
  - Higher $\sqrt{s}$ => better separation prompt and thermal photons
  - Stronger π^0 suppression => better S/Bg ratio

ALICE experiment



Photon measurement with ALICE



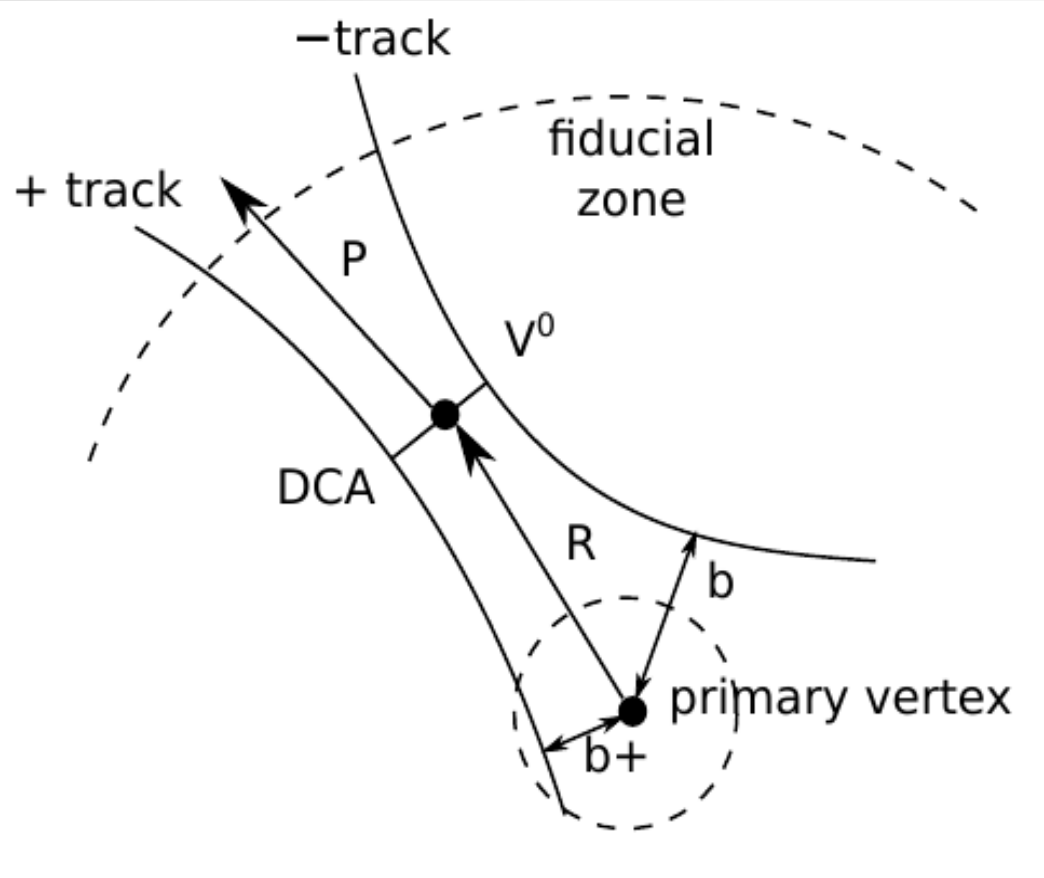
Photon Conversion Method (PCM)

- Good momentum resolution at low p_T
- High momentum reach is limited only by statistics
- Low conversion probability (~8.5%), coverage of full azimuthal angle, $|\eta|<0.9$
- Low contamination of photon spectrum

PHOS

- Good energy resolution at high p_T
- High photon registration efficiency, limited azimuthal angle (100^o) and $|\eta|<0.135$

Reconstruction of converted photon



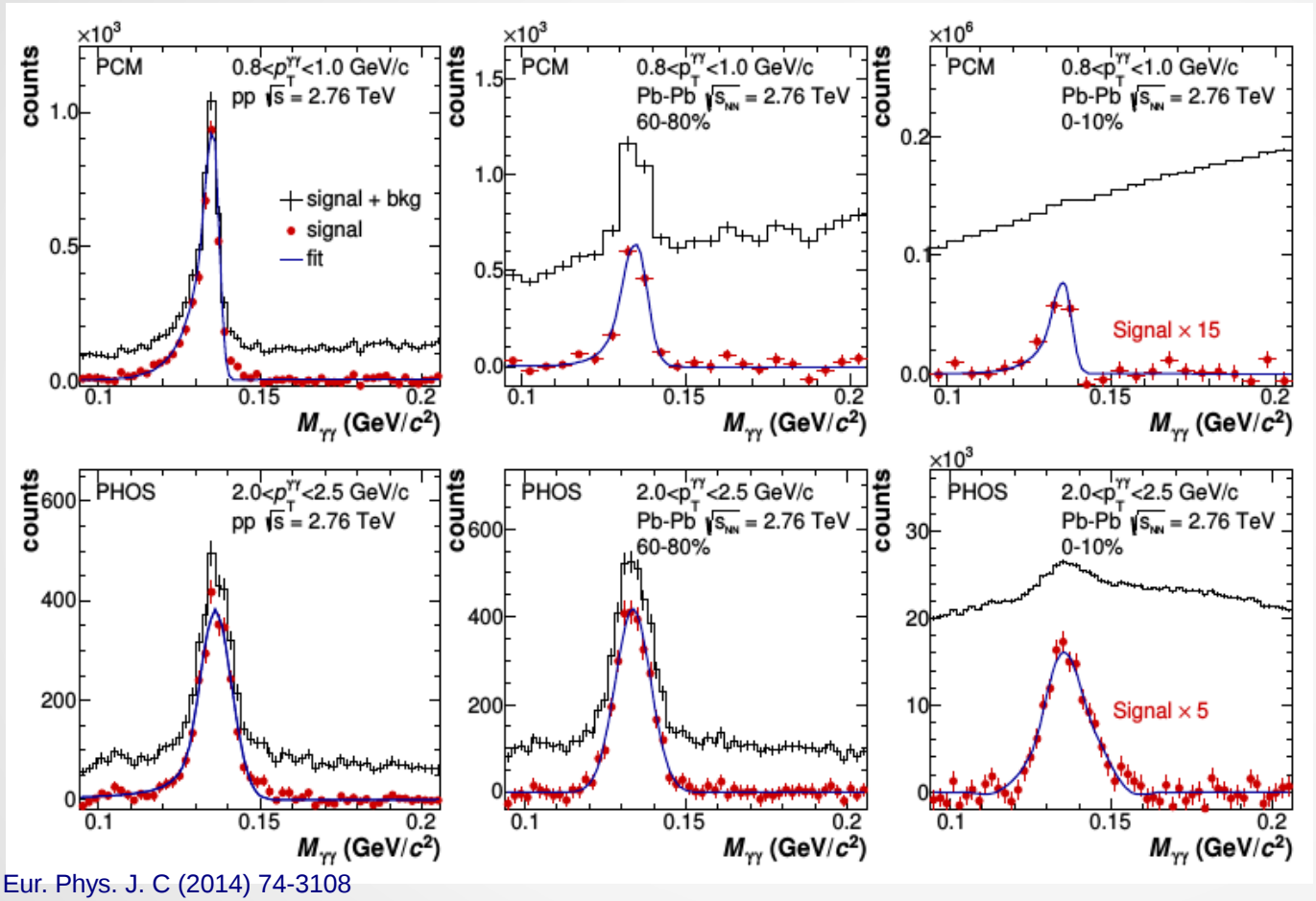
V0 algorithm

- Tracks with large impact parameters are paired
- Select pairs with small Distance of Closest Approach (DCA)
- Most abundant particle species K_s^0, Λ, $\overline{\Lambda}$, γ
- Photon conversion probability in $|\eta|<0.9$ up to R = 180 cm saturates at 8.5%

Photon identification

- Apply electron identification cuts
- Pair topology cuts

Measurement of π^0 spectrum

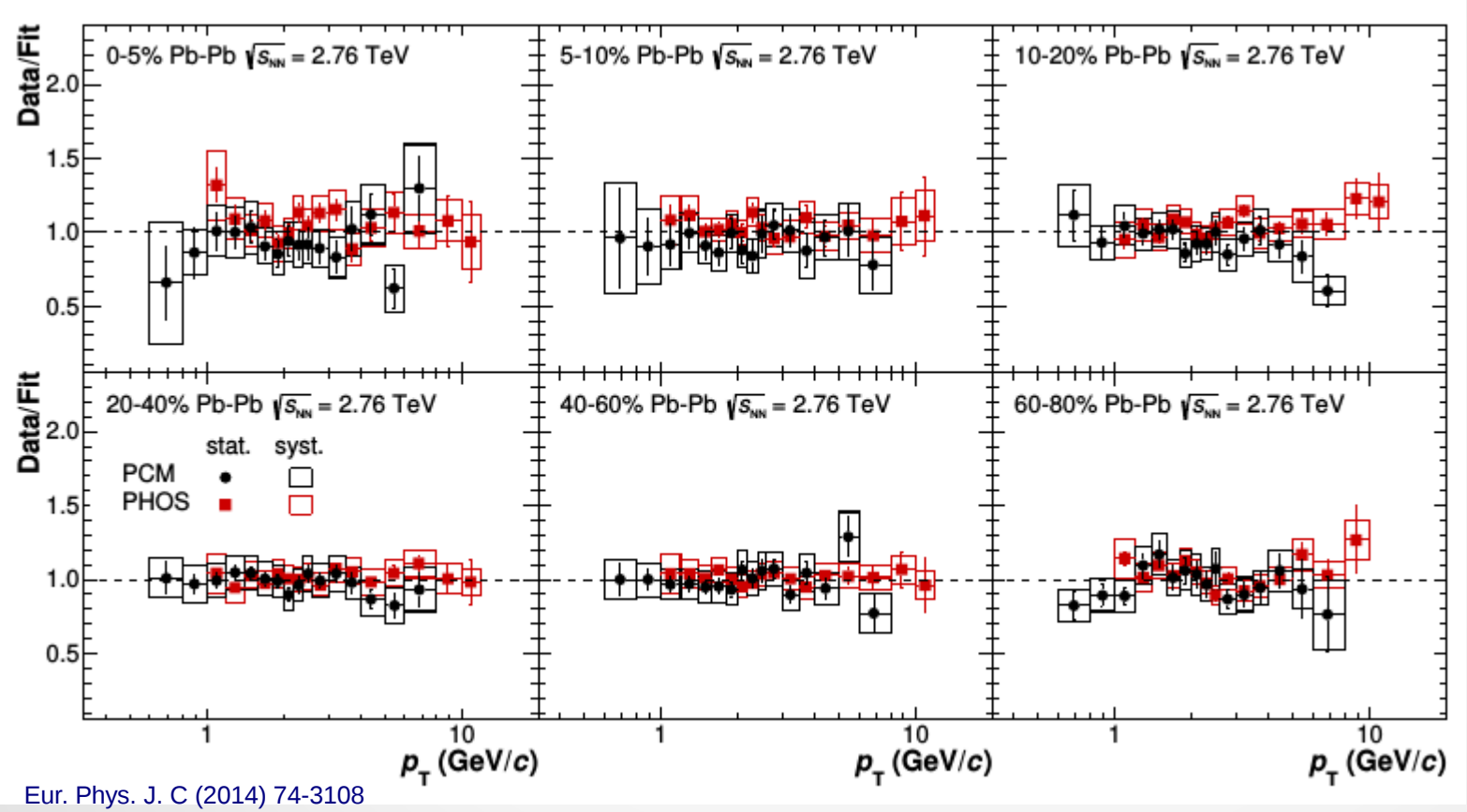


Eur. Phys. J. C (2014) 74-3108

π^0s are dominant source of decay photons
=> each detector measures π^0 spectrum independently to reduce sys. uncertainties

Both PCM and PHOS have comparable energy resolutions and dependence on multiplicity.

π^0 spectrum in Pb-Pb collisions



Eur. Phys. J. C (2014) 74-3108

Neutral pion spectra measured in Pb-Pb collisions with PCM and PHOS agree in all centrality bins.
Good cross-check of both measurements

Direct photon calculation

$$\gamma_{direct} = \gamma_{incl} - \gamma_{decay}$$

γ_{incl} – measured photon spectrum

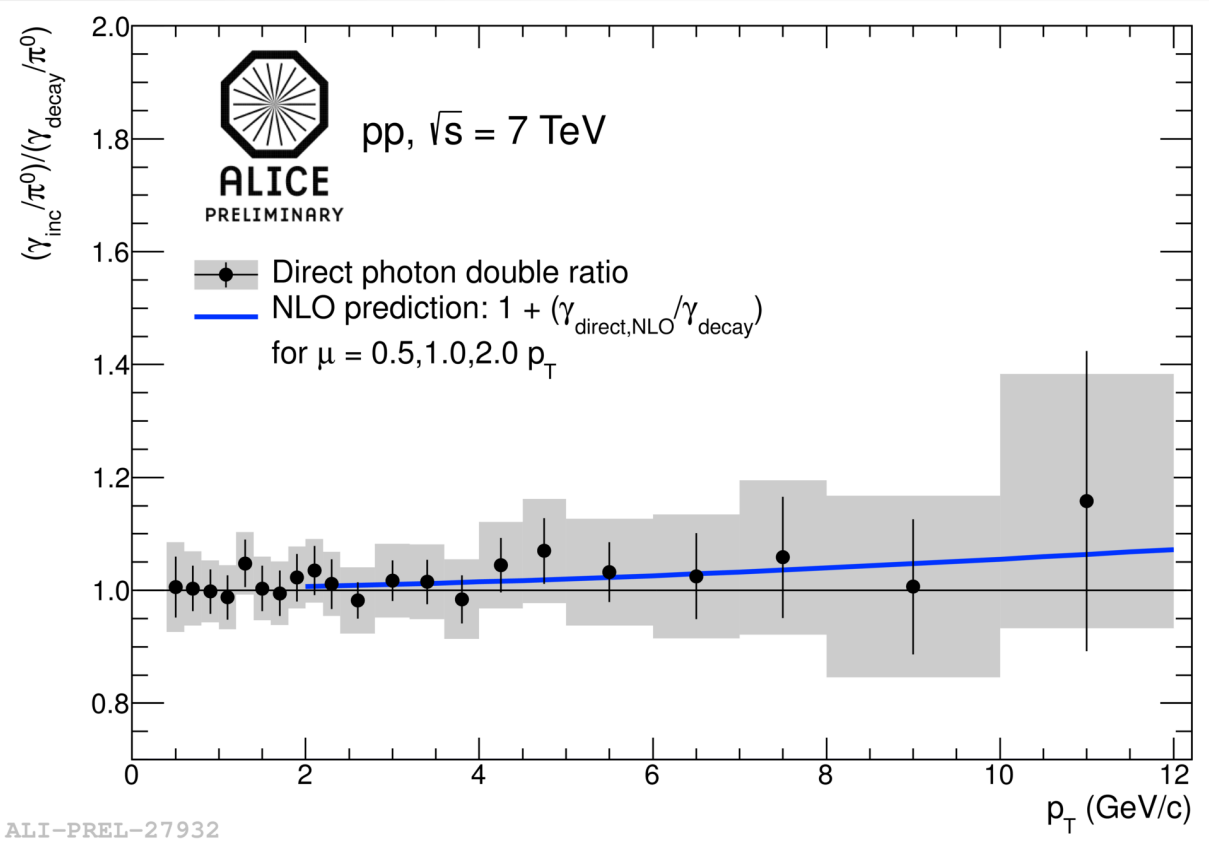
γ_{decay} – decay photon spectrum, estimated from cocktail simulation

$$R_\gamma = \frac{\gamma_{incl}/\pi^0_{meas}}{\gamma_{decay}/\pi^0_{cocktail}} \approx \frac{\gamma_{incl}}{\gamma_{decay}}$$

Some uncertainties cancel in double ratio. Facilitates normalizations of decay photon spectrum.

$$\gamma_{direct} = \gamma_{incl} - \gamma_{decay} = \left(1 - \frac{1}{R_\gamma}\right)\gamma_{incl}$$

Double ratio and spectrum in pp



Analyzed statistics $3.8 \cdot 10^8$ Min.Bias events

In the ratio uncertainties related to:
- normalization,
- π^0 measurement,
- reconstruction efficiency

partially or exactly canceled

Measurement is consistent with zero direct photon yield

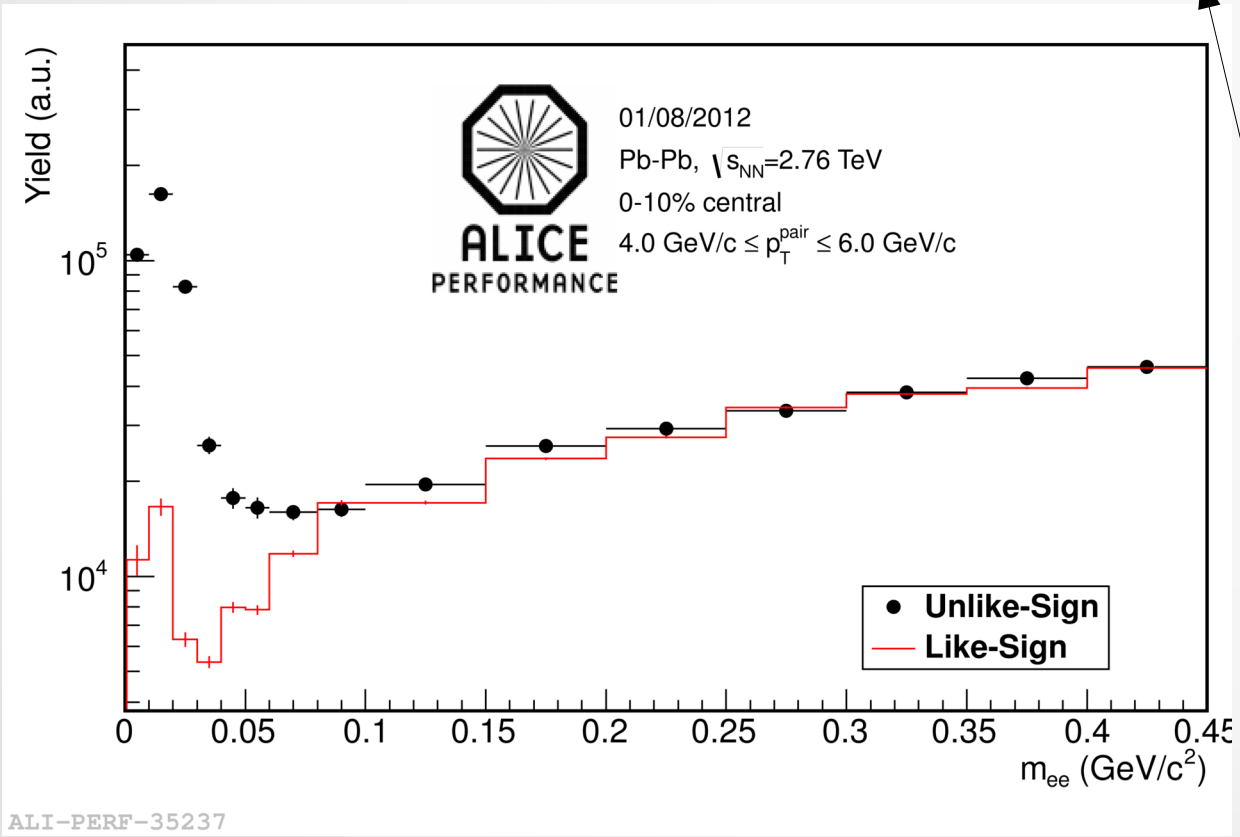
$$R_{NLO} = 1 + \frac{\gamma_{direct,NLO}}{\gamma_{decay}}$$

Measurement is consistent with NLO predictions

Low mass virtual photons (e^+e^-)

$$\frac{1}{N_\gamma}\frac{dN}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}\left(1-\frac{M_{ee}^2}{M^2}\right)^3 |F(M_{ee}^2)|^2$$

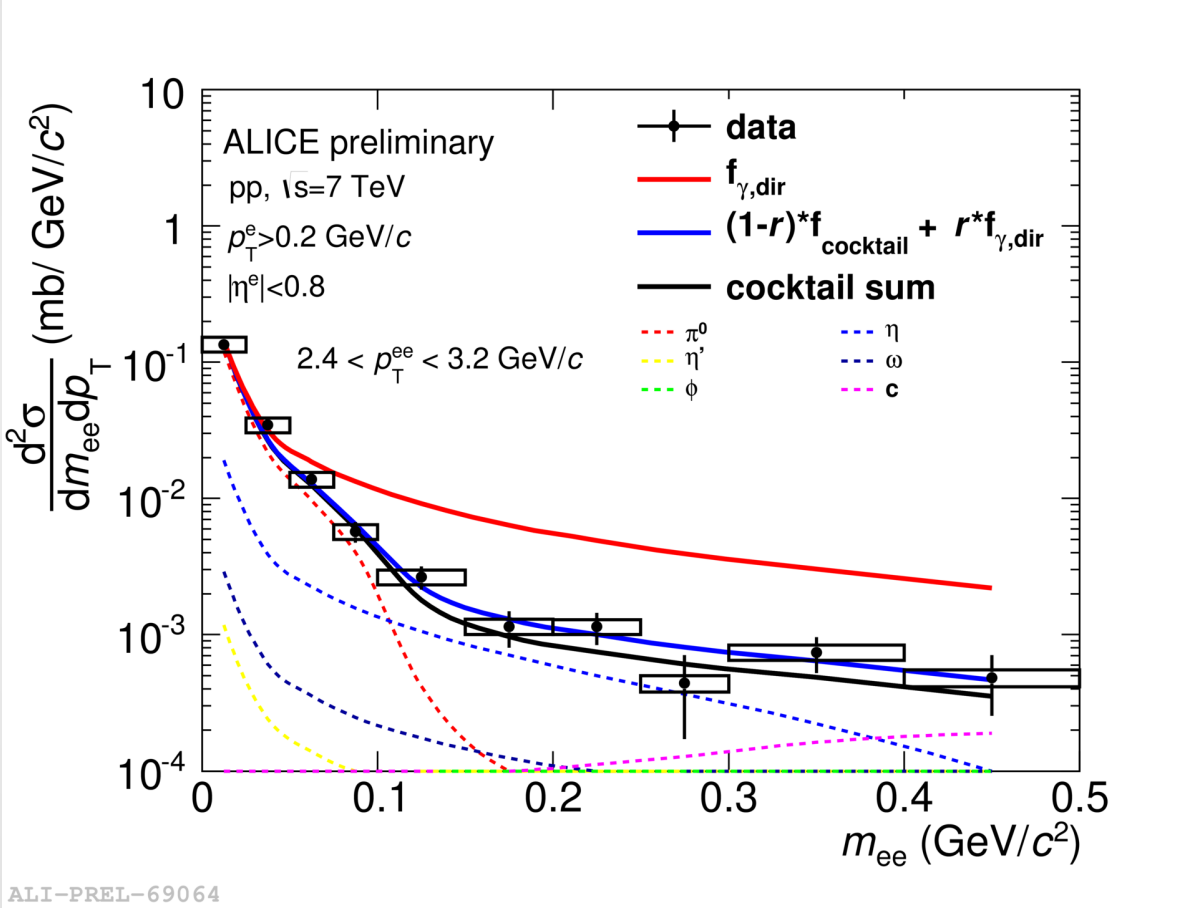
N.M.Kroll and W.Wada, Phys. Rev. 98 (1955) 1355.



(+) π^0 contribution decrease with increase of m_{ee}

(-) big combinatorial background, rapidly increasing with multiplicity

Extraction direct photon contribution



$3 \cdot 10^8$ MinBias pp events (2010 sample)

$\mathbf{f}_{\gamma,combined}$ – measured distribution with subtracted combinatorial background

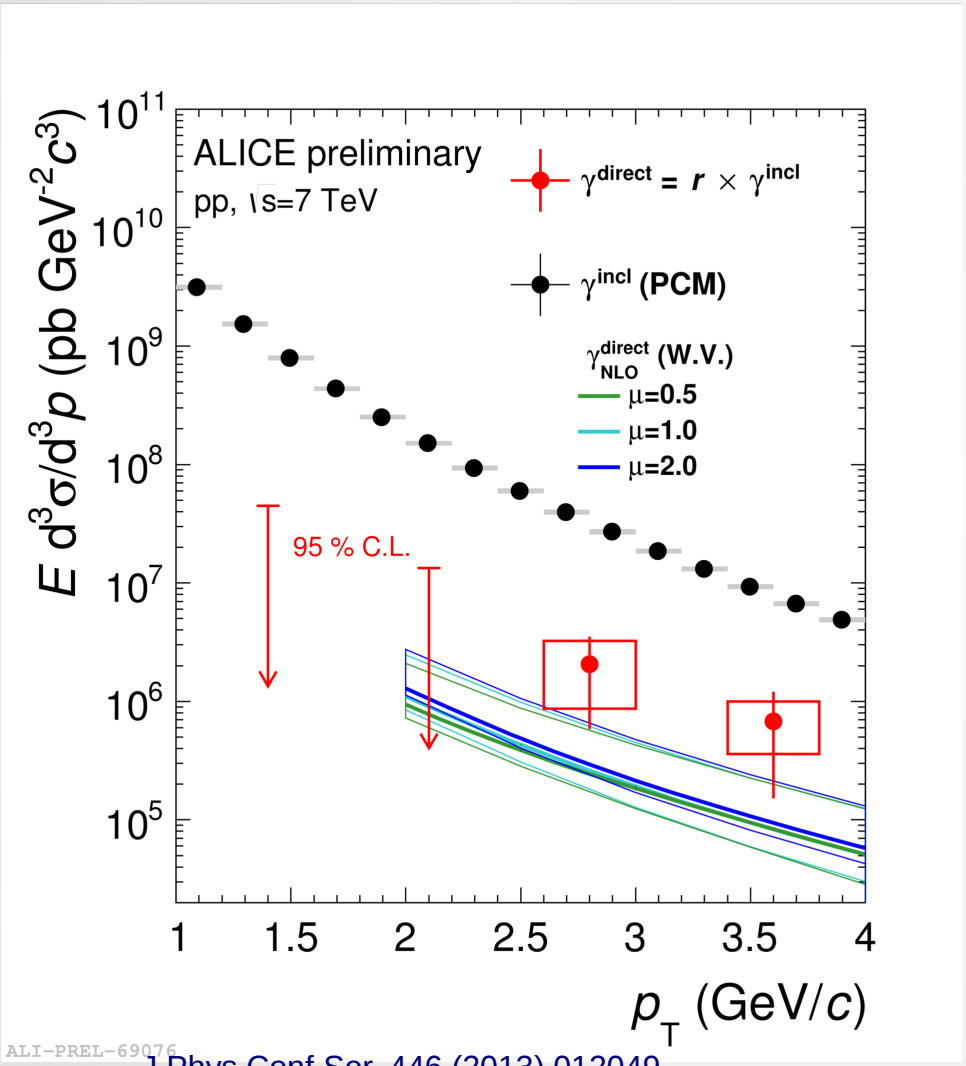
$\mathbf{f}_{\gamma,decay}$ – estimated shape of hadronic decays contribution

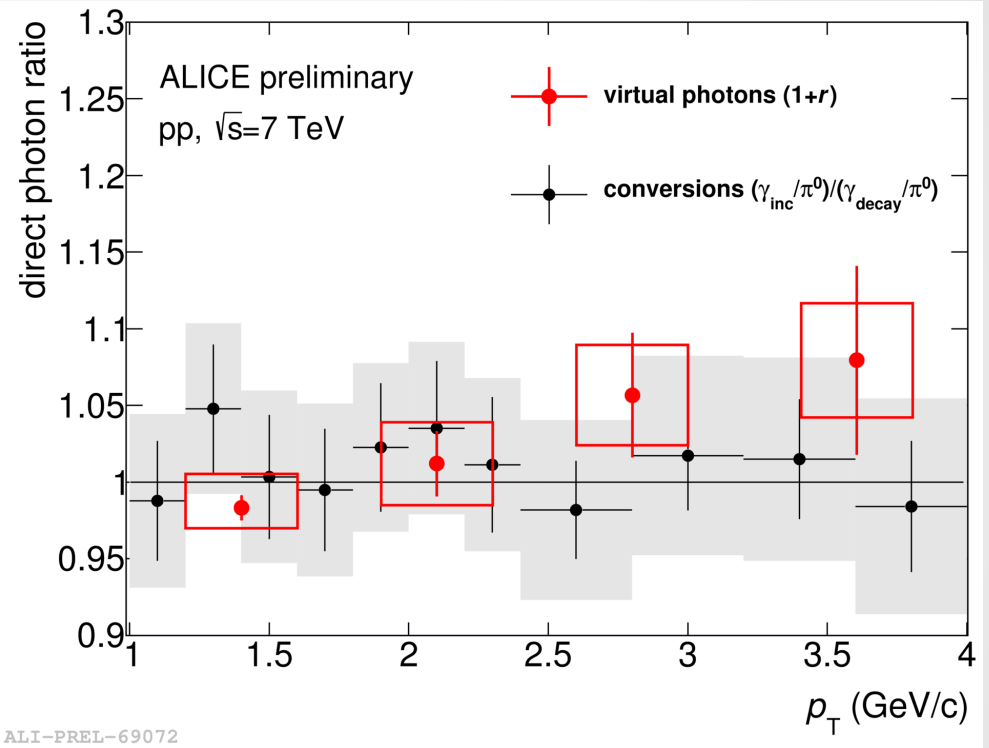
$\mathbf{f}_{\gamma,decay}$ – estimated shape of direct virtual photon contribution

$$f_{\gamma,combined} = (1-r) f_{\gamma,decay} + r f_{\gamma,dir}$$

$$r = \frac{\gamma_{dir}}{\gamma_{incl}}$$

Direct photons in pp at √s= 7 TeV

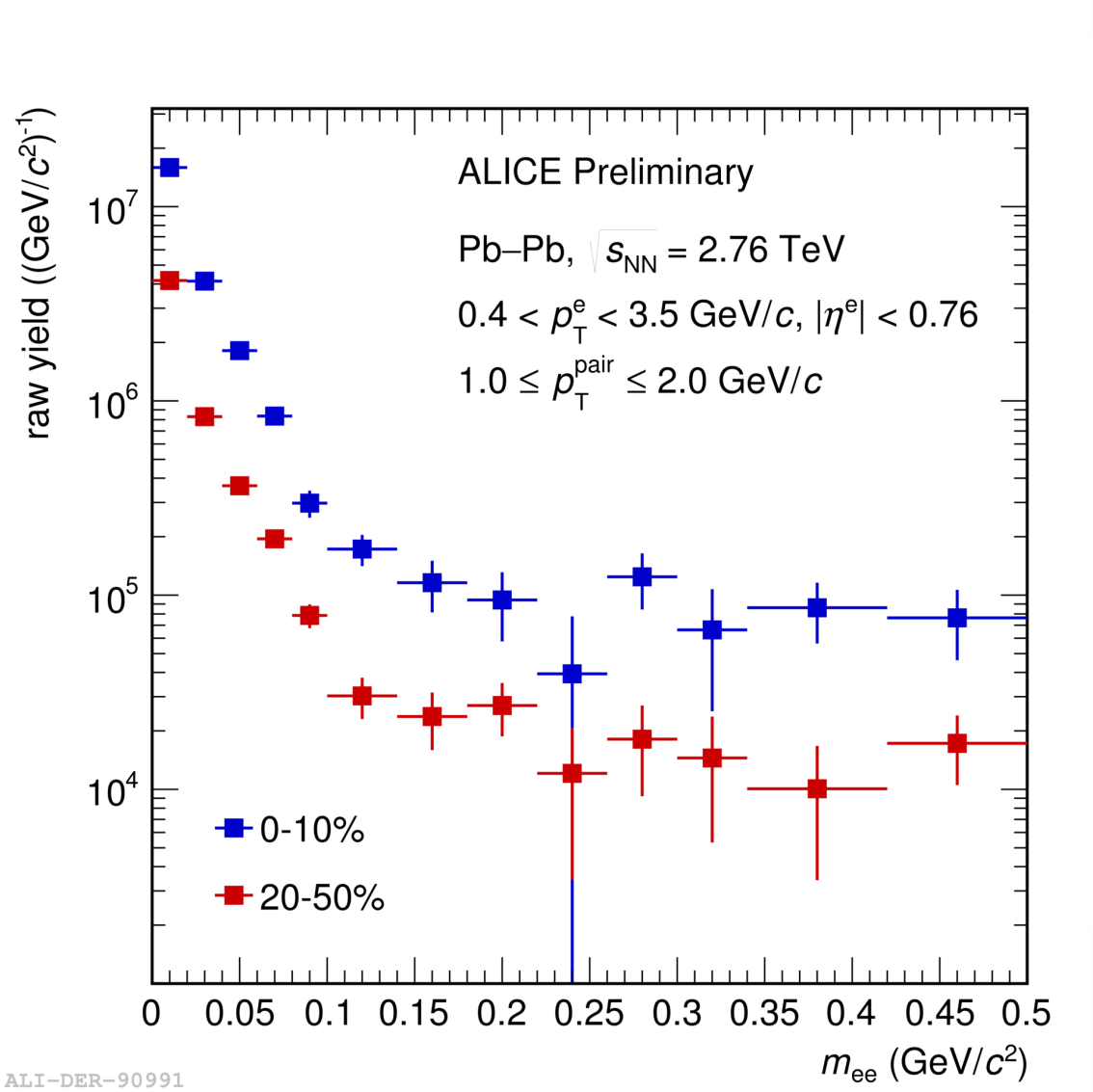




Virtual and real photon measurements agree within uncertainties

J.Phys.Conf.Ser. 446 (2013) 012049
J.Phys.Conf.Ser. 612 (2015) 1, 012028

Virtual photons in Pb-Pb

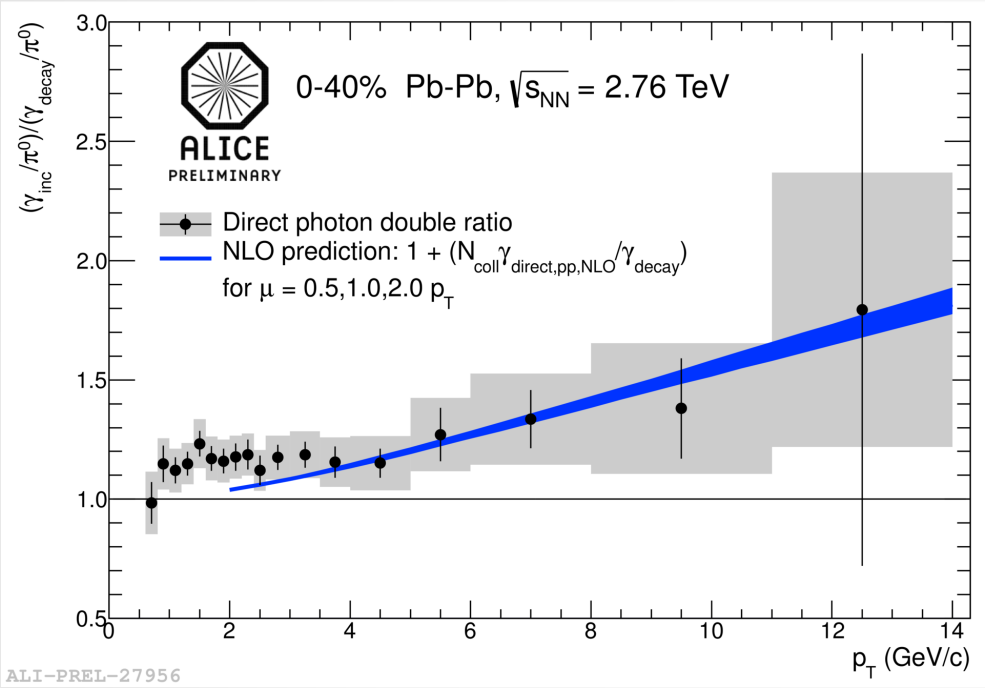


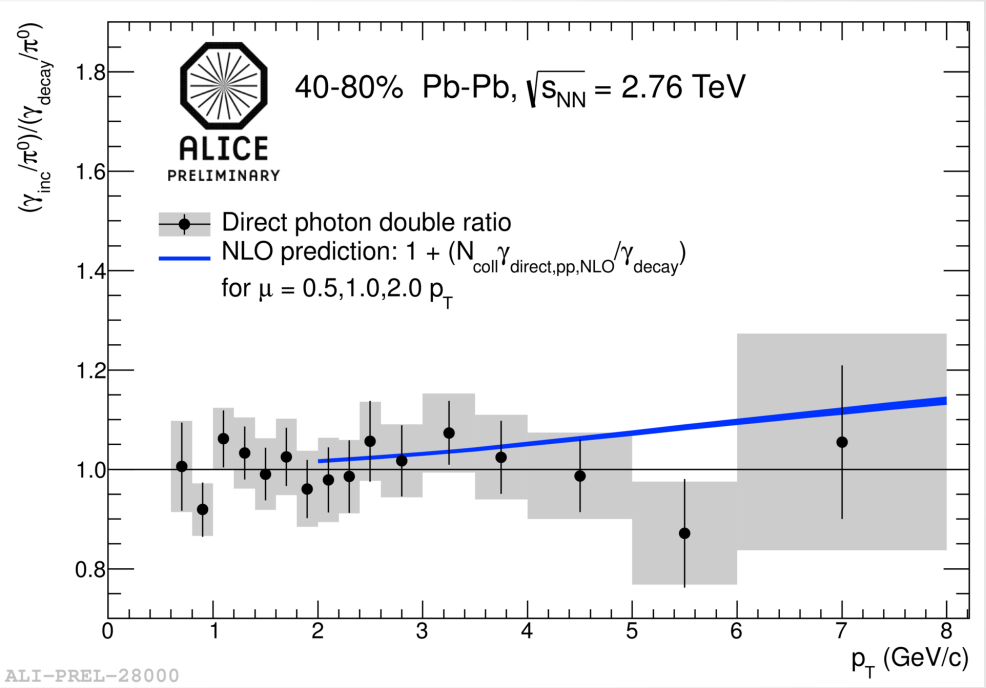
Full Run1 statistics.

Huge combinatorial background: after subtraction only wide p_T bins can be analyzed.

Analysis is ongoing....

Double ratio in Pb-Pb





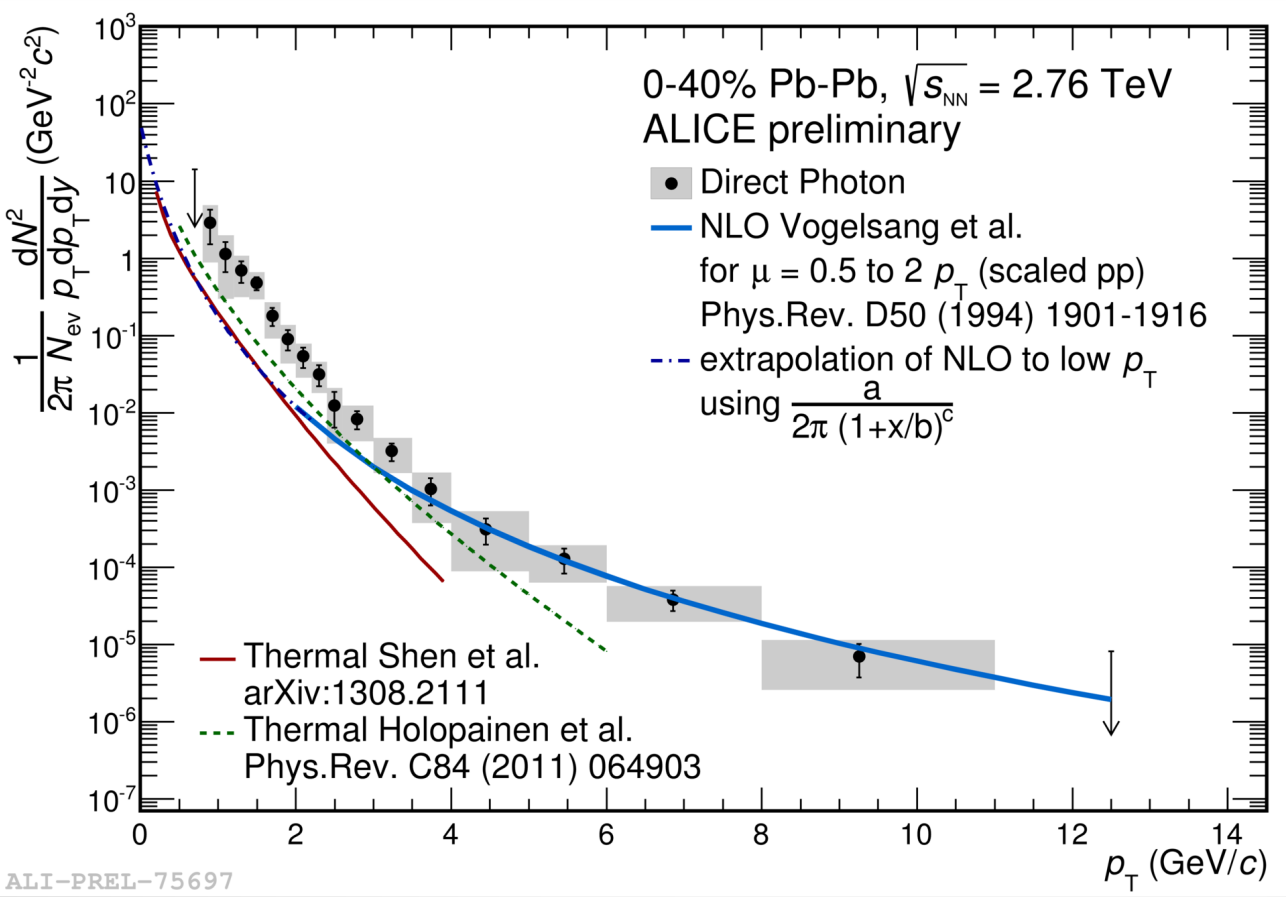
In **central** collisions

- double ratio agrees with N_{col} scaled pp NLO predictions;
- at low p_T<2 GeV/c there is a ~20% excess w.r.t. NLO predictions.

In **peripheral** events

- double ratio is consistent with no direct photon excess at any p_T;
- double ratio is also consistent with N_{col} scaled pp NLO predictions

Direct photon spectrum in Pb-Pb



$$N_\gamma^{dir} = \left(1 - \frac{1}{R}\right) N_\gamma^{incl}$$

At high p_T>4 GeV/c spectrum agrees with N_{col} scaled NLO pp predictions.

Intermediate region – interplay between prompt and thermal (jet conversion, …?) contributions.

Both theoretical estimates of thermal photon yield underestimate data by factor 2-10 at low p_T<2 GeV/c.

Direct photon collective flow

Inclusive photon collective flow contains contributions from direct and decay photons:

$$v_n^{incl} = \frac{N_\gamma^{dir}}{N_\gamma^{incl}} v_n^{\gamma,dir} + \frac{N_\gamma^{decay}}{N_\gamma^{incl}} v_n^{\gamma,decay}$$

With the double ratio R and decay photon flow calculated from cocktail, one can estimate the direct photon flow:

$$v_n^{\gamma,dir} = \frac{R\, v_n^{\gamma,incl} - v_n^{\gamma,decay}}{R-1}$$

Inclusive photon flow extraction

Collective flow is estimated using event plane method.
Inclusive photon flow is decomposed as

$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left(1 + \sum_n 2 v_n \cos\left(n\left(\varphi - \Psi_{RP}\right)\right)\right)$$

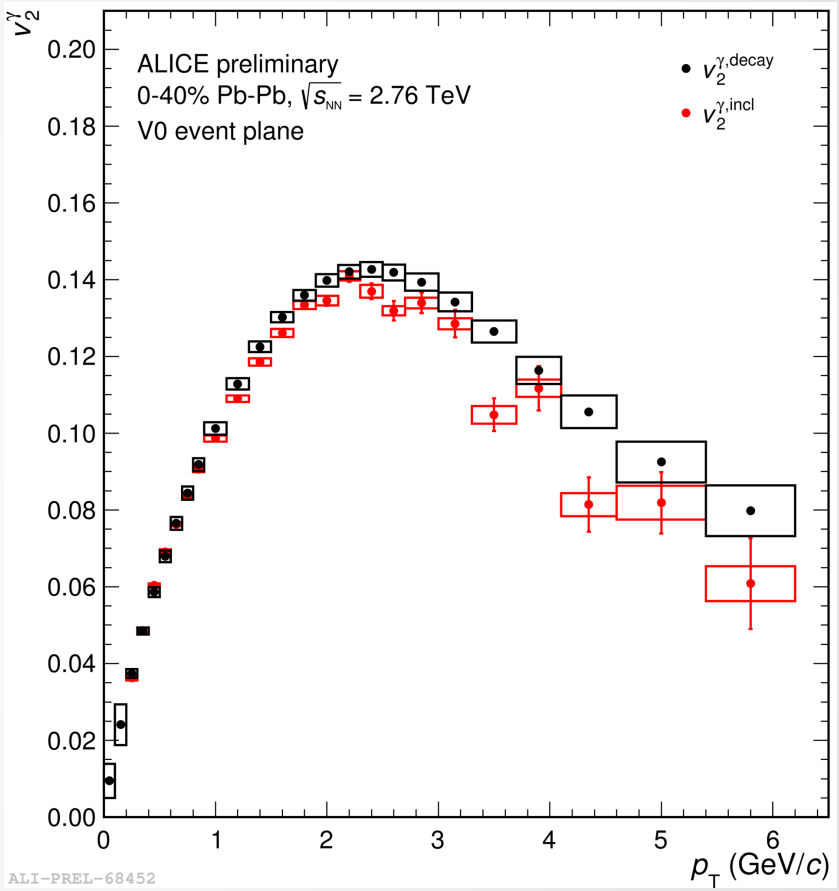
where reaction plane is measured with one of 3 detectors

VZEROA: 2.8<η< 5.1
VZEROC: -3.7<η<-1.7
TPC: -0.9<η< 0.9

Event plane resolution was estimated using 3-subevent method.

Cocktail simulations:

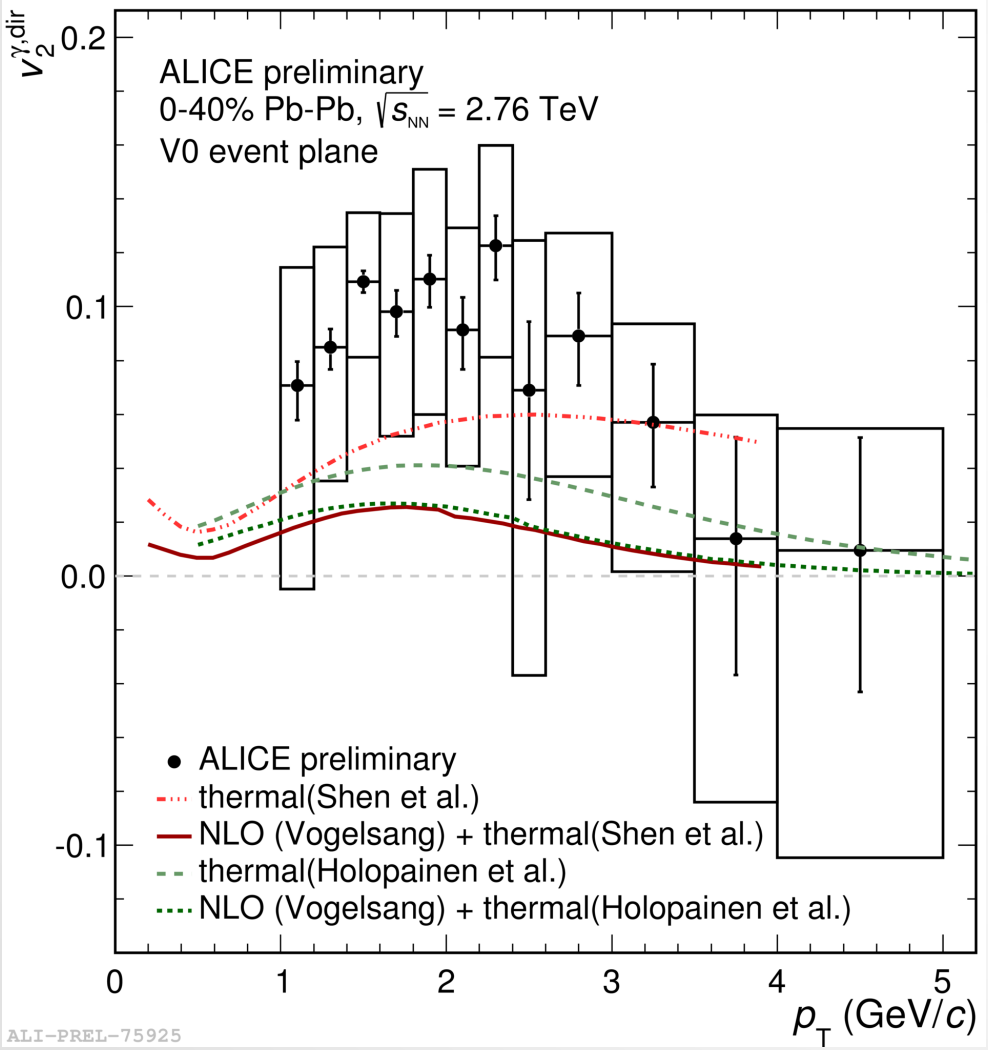
Use $\pi^{\pm}$ flow for estimate π^0 one
Use KE_T scaling for other mesons

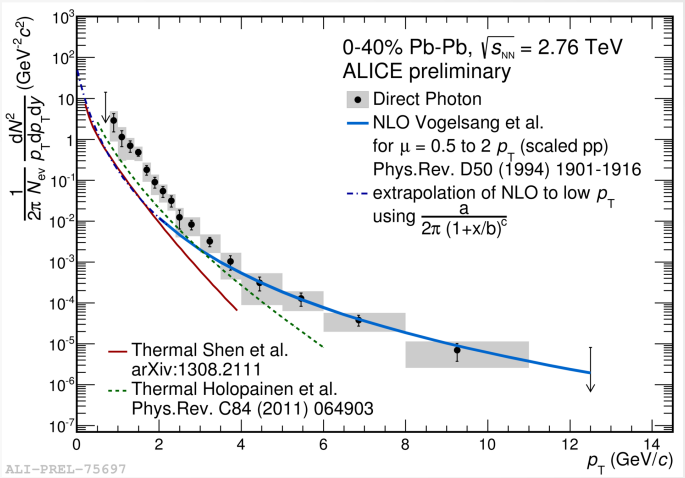


Above 3 GeV/c inclusive photons significantly smaller than decay photons

Below 3 GeV/c consistent within uncertainties

Direct photon flow v_2



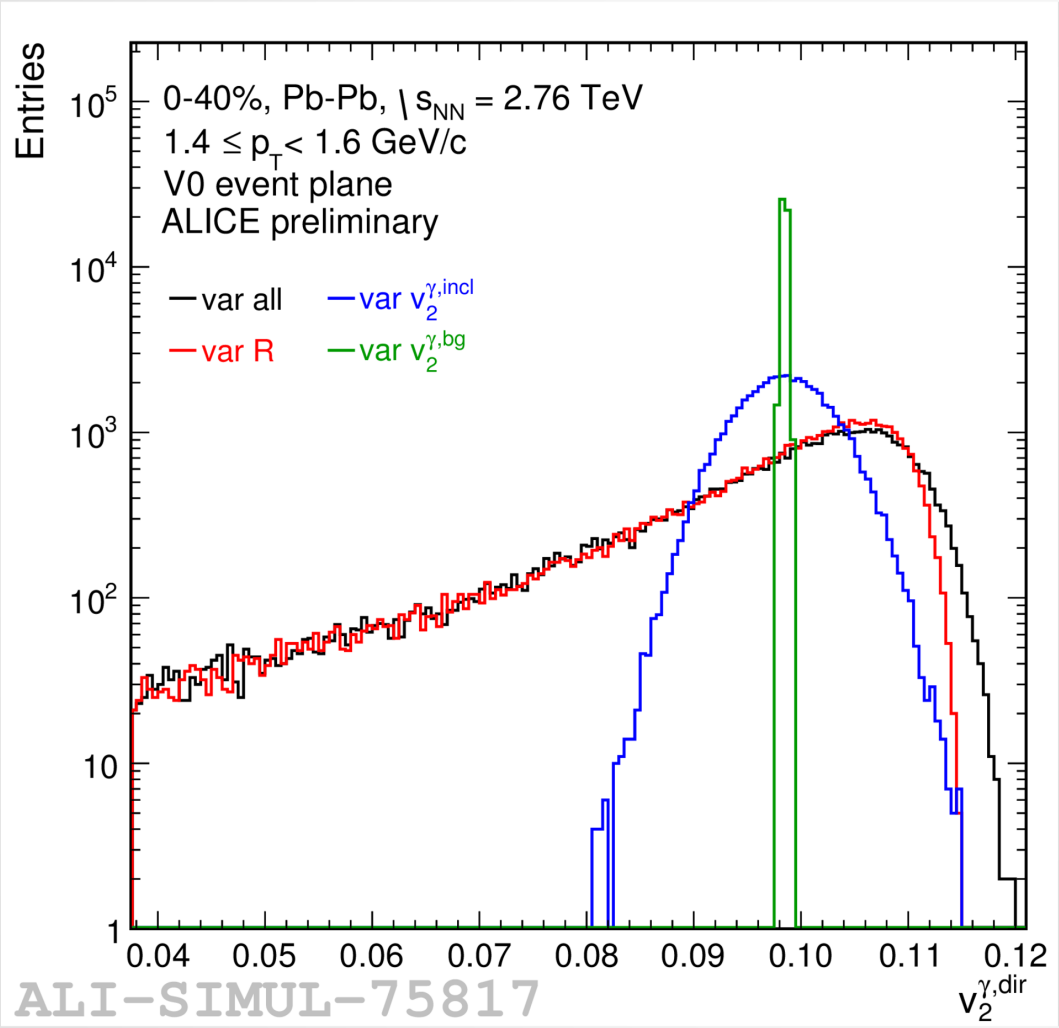


Similar to the yield, direct photon flow at low p_T<2 GeV/c is underestimated by theory calculations by a factor 2-10.

Difference between data and theory is ~1-2 sigma: not very significant

Careful error treatment is necessary

Error propagation

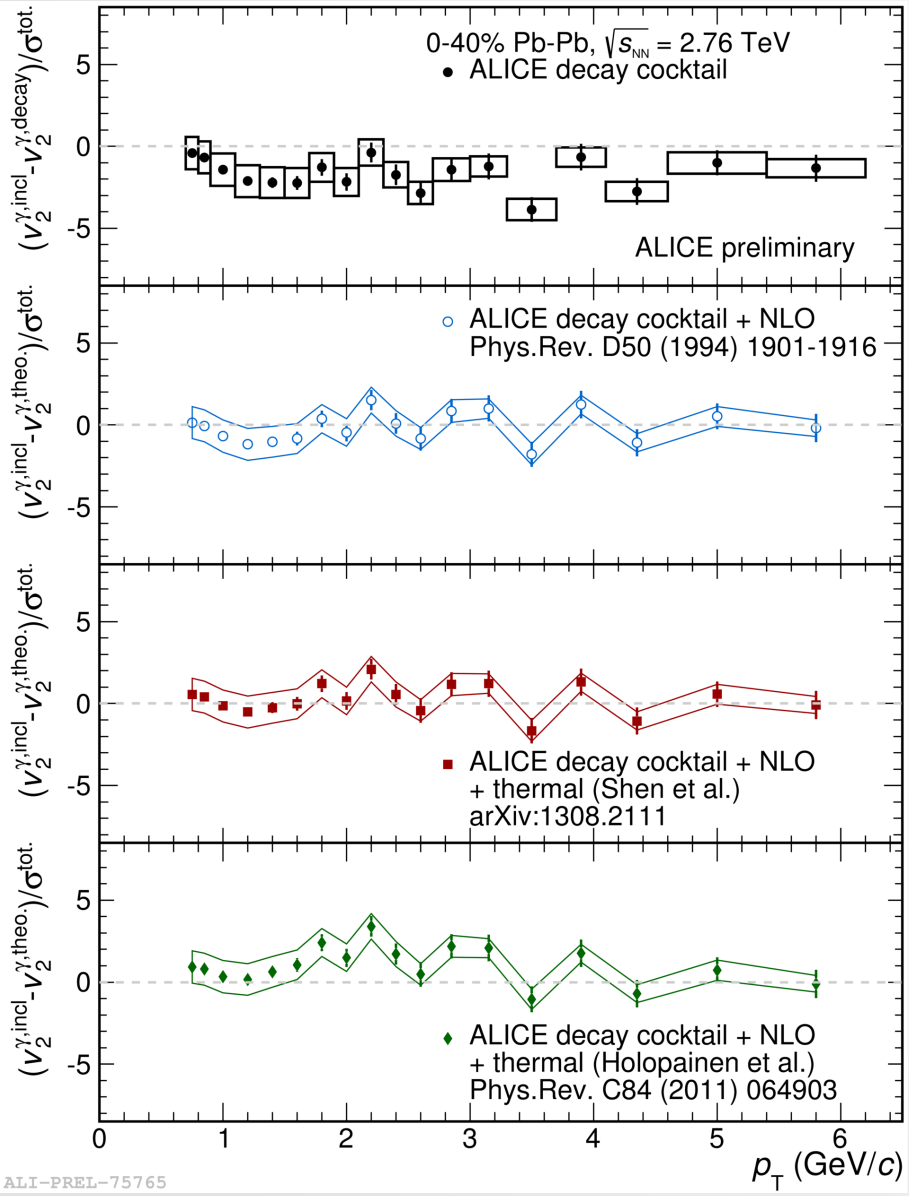


$$v_n^{\gamma,dir} = \frac{R\, v_n^{\gamma,incl} - v_n^{\gamma,decay}}{R-1}$$

Assume R, v_2^{incl}, v_2^{decay} to be independent with uncertainties described by Gaussians.

Due to the pole (R-1) resulting (lower) distribution for v_n^{dir} will not be Gaussian.

v_2 comparison



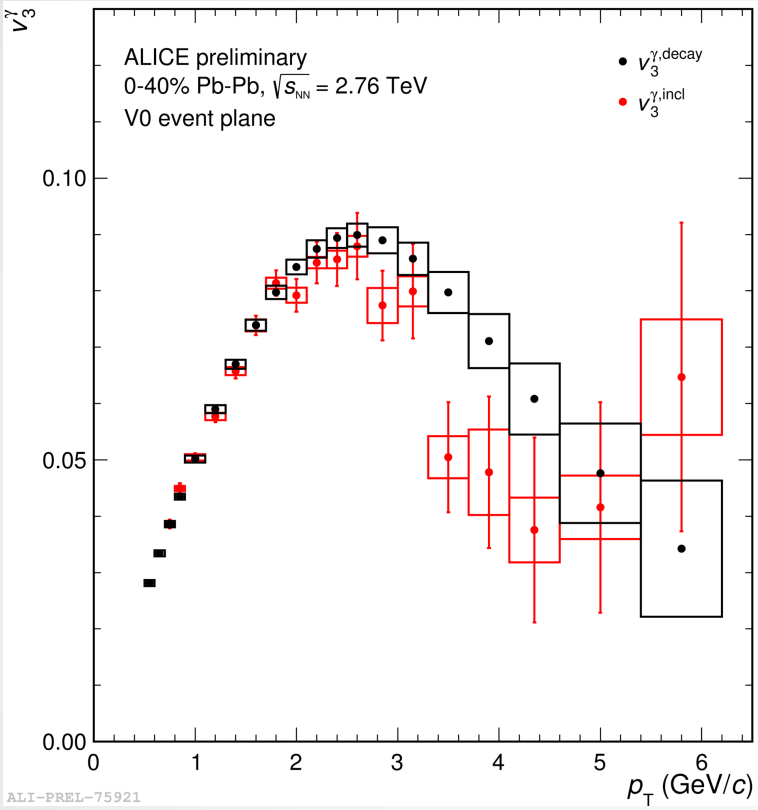
Compare inclusive photon flow

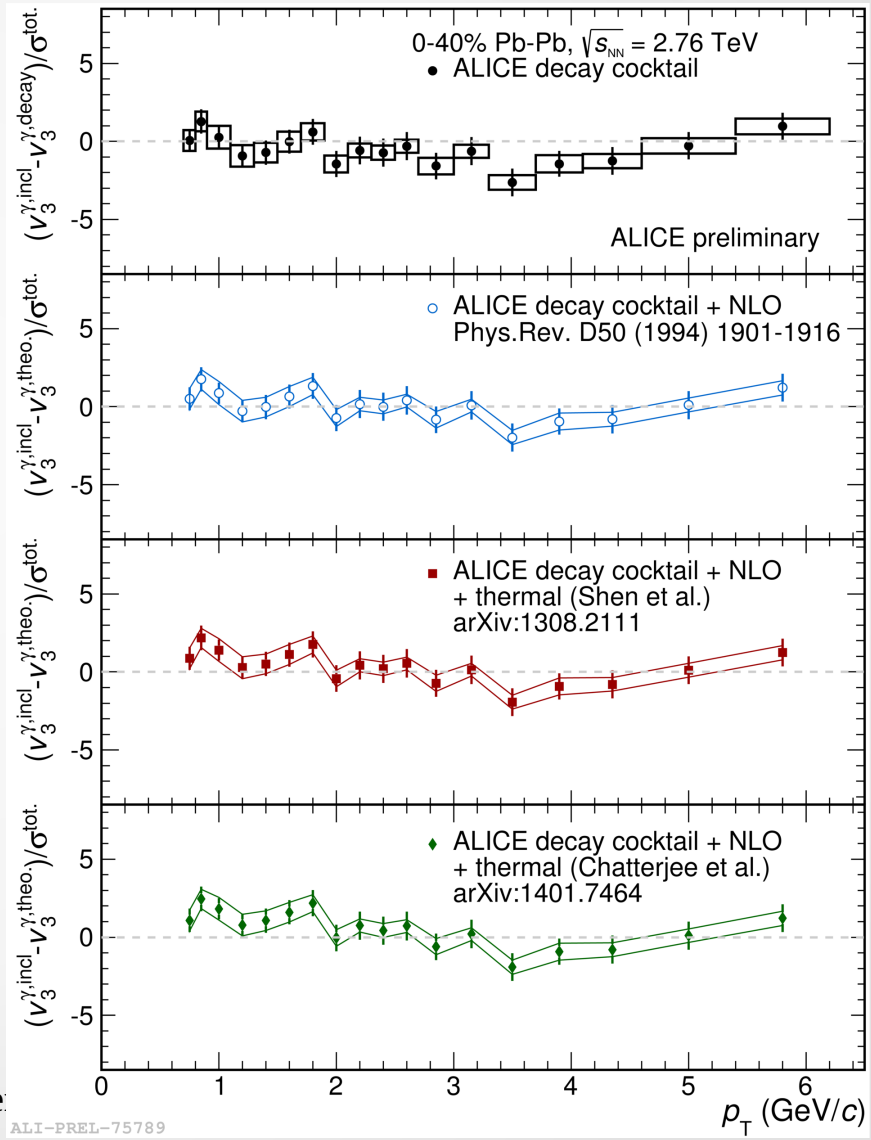
$$\left(v_2^{\gamma,incl} - v_2^{\gamma,model}\right)/\sigma_{total}$$

where for $v_2^{\gamma,model}$ one can use cocktail, cocktail+theory etc.

- Cocktail does not reproduce $v_2^{\gamma,incl}$
- Cocktail+NLO agree with data
- Cocktail+NLO+thermal (Shen et al.) agree with data
- Cocktail+NLO+thermal (Holopainen et al.) somewhat under predict v_2

Triangular flow





Similar to elliptic flow, $v_3^{\gamma,incl}$ Is not reproduced by cocktail $v_3^{\gamma,decay}$.

All models failed to reproduce $v_3^{\gamma,incl}$ at low p_T<1 GeV/c.

Conclusions

- Direct photon spectrum in pp collisions at $\sqrt{s}$=7 TeV was measured with real and virtual photons. Double ratios obtained with two methods agree with each other and with NLO predictions.
- Photon double ratios were measured in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV.
  - In peripheral 40-80% collisions R_γ agrees both with no direct photon access and with scaled NLO predictions.
  - In central 0-40% collisions R_γ agrees with N_{col} scaled NLO predictions at high p_T>4 GeV/c
  - An excess ~20% compared to N_{col} scaled NLO predictions in R_γ has been measured in 0-40% central Pb–Pb collisions at p_T<2 GeV/c
- A direct photon v_2 which is of similar size as the charged hadron flow has been measured in 0-40% Pb–Pb collisions
- The magnitude of the systematic errors and the propagation of the errors from the Rγ to both measurements was discussed
- A different method to compare data and theory for inclusive photon v_2 & v_3 measurements avoiding pole $1/(R_\gamma-1)$ was presented.

Backup slides

Cocktail

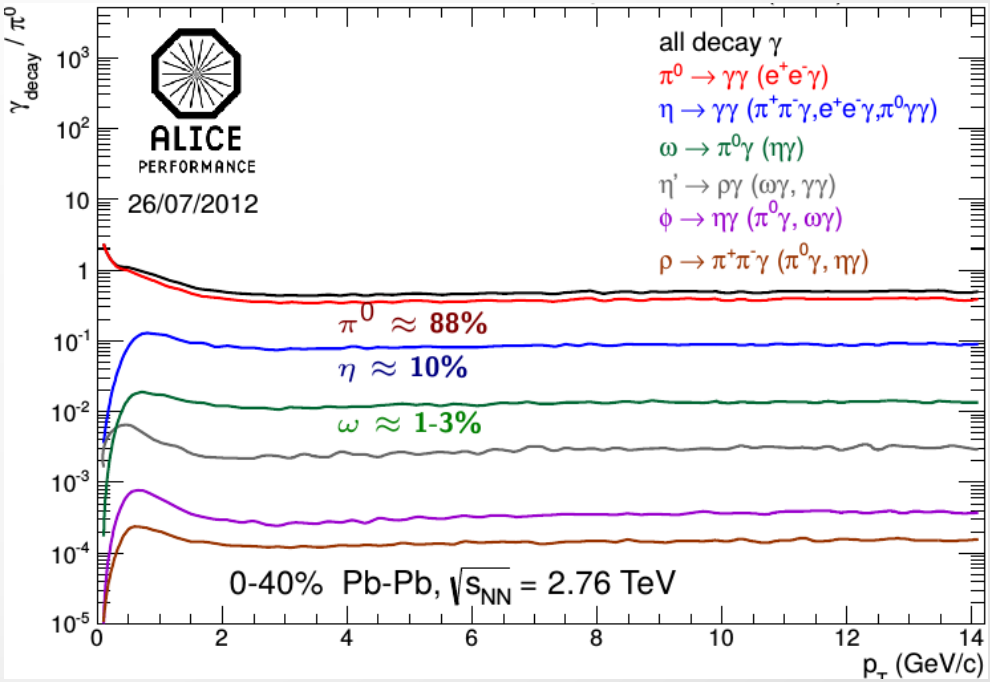
Meson (C_m)	meas.	Mass	Decay Branch	B. Ratio
π^0	pp, Pb–Pb	134.98	$\gamma\gamma$ $e^+e^-\gamma$	98.789% 1.198%
η (0.48)	pp	547.3	$\gamma\gamma$ $\pi^+\pi^-\gamma$ $e^+e^-\gamma$	39.21% 4.77% $4.9 \cdot 10^{-3}$
ρ^0 (1.0)		770.0	$\pi^+\pi^-\gamma$ $\pi^0\gamma$	$9.9 \cdot 10^{-3}$ $7.9 \cdot 10^{-4}$
ω (0.9)	pp	781.9	$\pi^0\gamma$ $\eta\gamma$	8.5% $6.5 \cdot 10^{-4}$
η' (0.25)		957.8	$\rho^0\gamma$ $\omega\gamma$ $\gamma\gamma$	30.2% 3.01% 2.11%
ϕ (0.35)	pp, Pb–Pb	1019.5	$\eta\gamma$ $\pi^0\gamma$ $\omega\gamma$	1.3% $1.25 \cdot 10-3$ $< 5\%$
Σ^0 (1.0)		1192.6	$\Lambda\gamma$	100%

m_T-Scaling:
Same shape of cross sections, $f(m_T)$, of various mesons

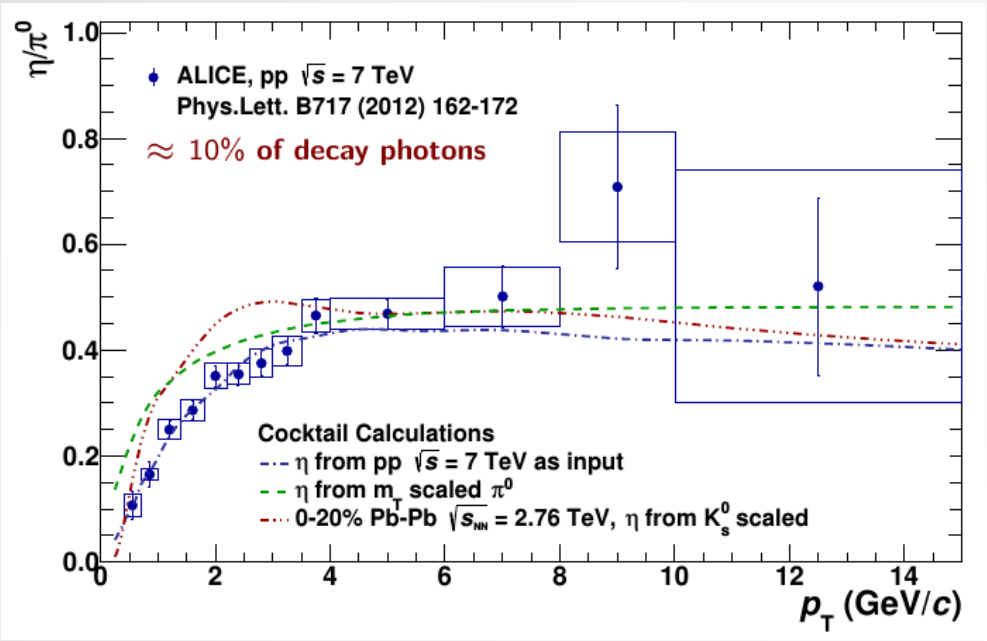
$$E\frac{d^3\sigma_m}{dp^3} = C_m \cdot f(m_T)$$

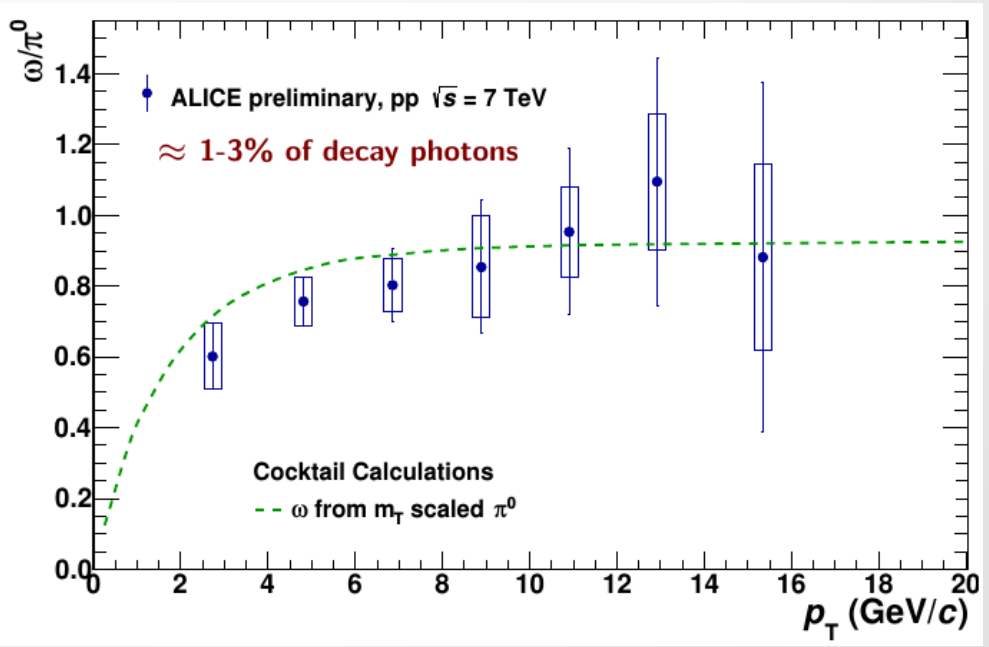
Use fit to measured π^0 (Pb–Pb, pp) and η (pp)

Other particle spectra obtained via m_T-scaling of measured π^0



Check of m_T scaling

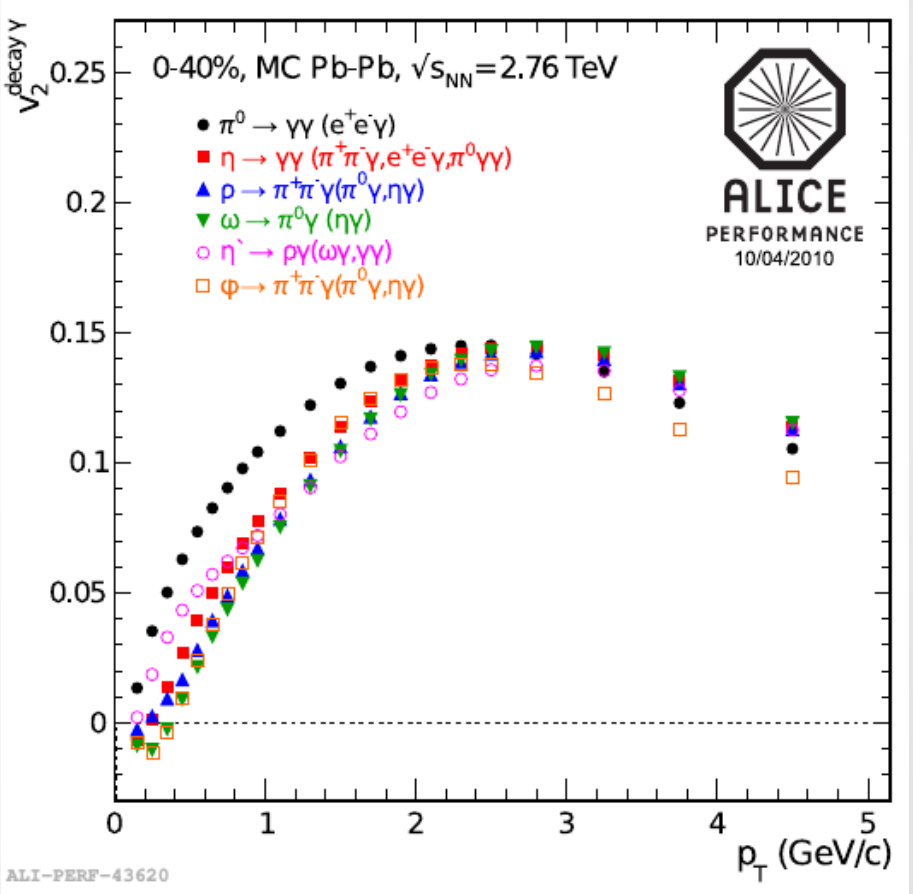




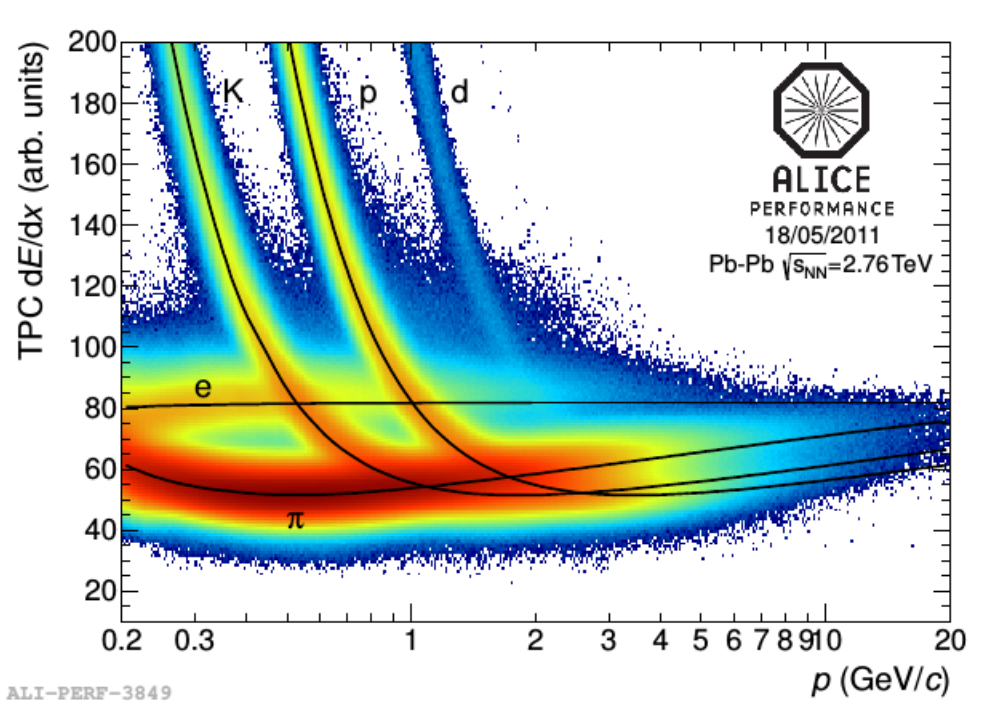
Cocktail: decay photon flow

Use charged pion v_n to estimate π^0 v_n
(flows agree within uncertainties)

KE_T scaling: v_n of mesons scales with KE_T
$KE_T = m_T - m$



Electron selection criteria



Global Electron Selection Criteria

- Both tracks originate from the same V0 candidate
- No kinks
- Opposite charge
- Small R cut (R < 5 cm)
- TPC refit condition
- Minimum momentum of 50 MeV/c
- Minimum fraction of the TPC clusters with respect to findable clusters due to conversion radius

PID Based Selection Criteria

nσ around electron energy loss hypothesis in the TPC dE/dx
TOF electron nσ selection (if information available)

After PID ~ 80% pure photon sample

Pair selection criteria

Photon χ^2/ndf:

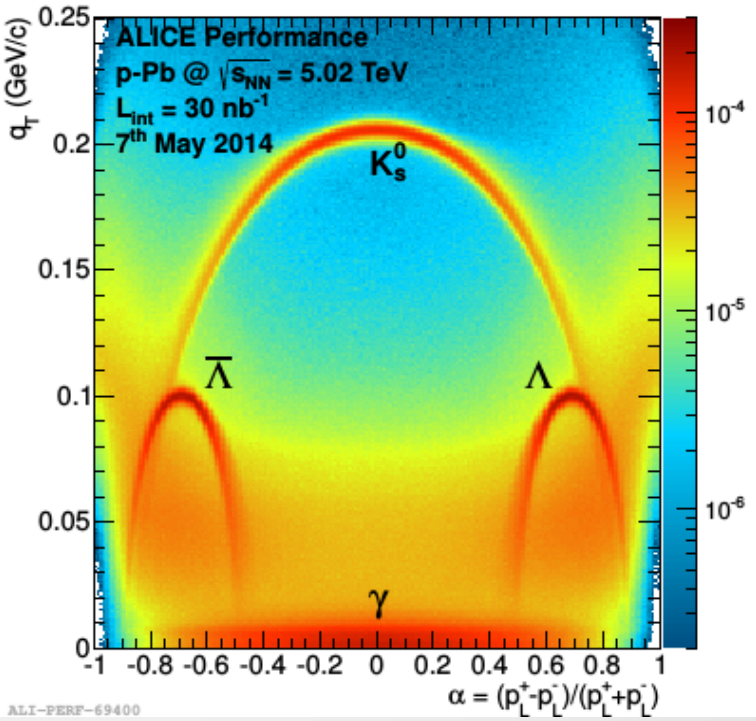
- Based on a Kalman-Filter (AliKFParticle package)
- Measure for conversion likelihood: includes: zero V0 mass, pointing to primary vertex, correct electron mass, mutual secondary vertex

Further Photon Selection Criteria:

- Crosschecks for std. photon criteria
- Psi-Pair angle
  opening angle perpendicular to B field
- Cosine of pointing angle
  pointing to the primary vertex

Photon q_T:

- Transv. mom. component of daughter relative to the V0
  $q_T = p \times \sin(\Theta_{\mathrm{mother-daughter}})$
- Clear separation of γ, Λ and K^0_s



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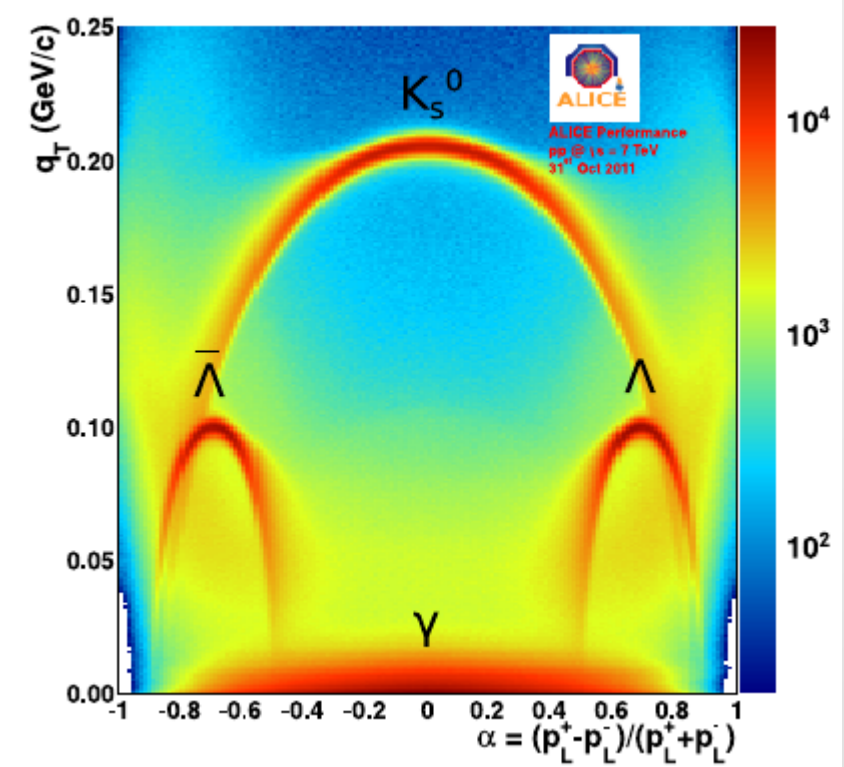

Further Photon Selection Criteria:
Crosschecks for std. photon criteria
Psi-Pair angle - opening angle perpendicular to B field
Cosine of pointing angle pointing to the primary vertex

Material Budget

Performance of the ALICE Experiment at the CERN LHC
arXiv:1402.4476 [nucl-ex]